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Petrogenesis of orbicular migmatites bordering the Idaho batholith Shoup Idaho

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THE PETROGENESIS OF ORBICULAR MIGMATITES
BORDERING THE IDAHO BATHOLITH, SHOUP, IDAHO

By

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CHAPTER I

INTRODUCTION

Previous Research

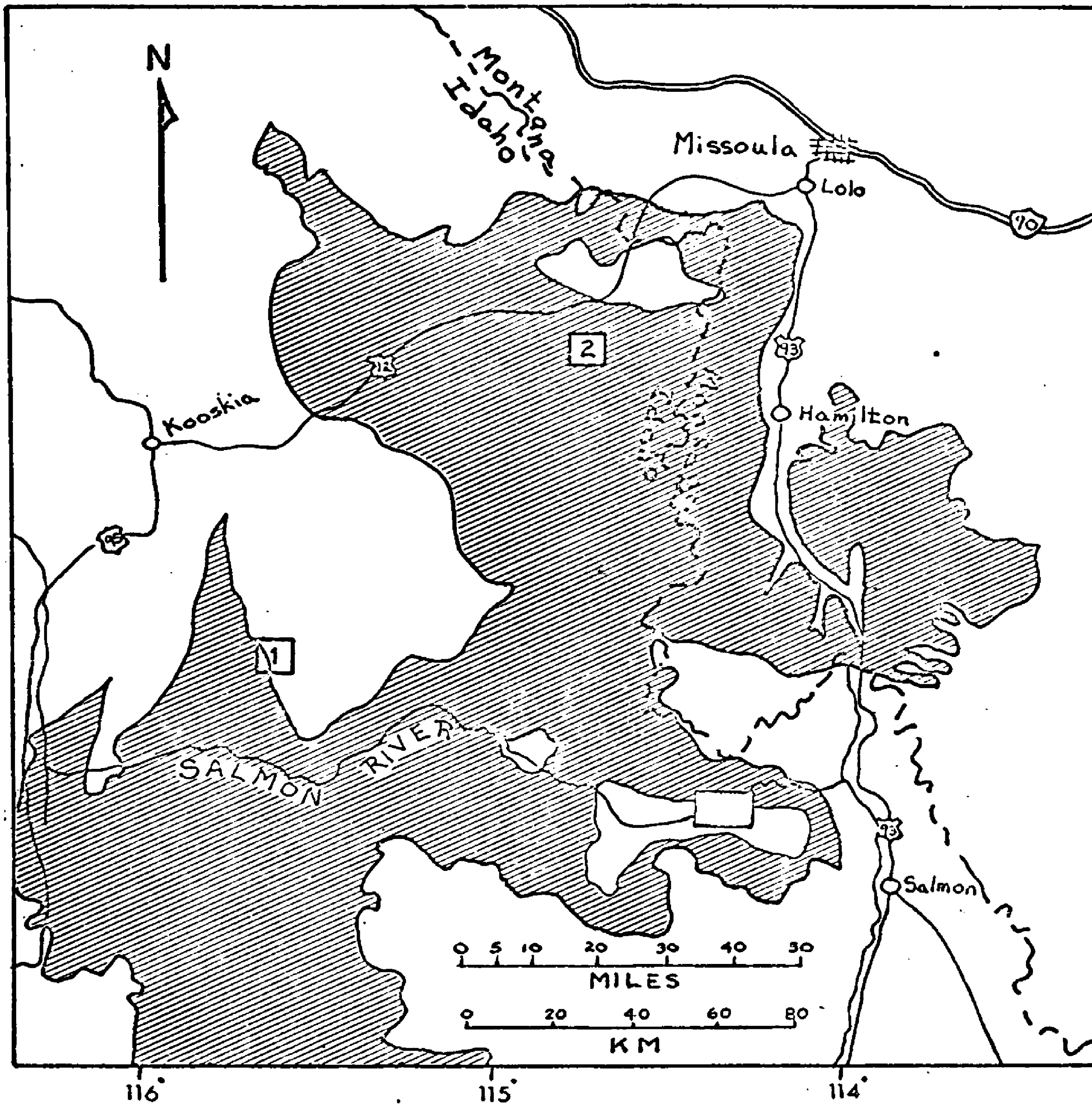
Orbicular rocks have received attention from geologists since the early nineteenth century and are distributed worldwide. Most commonly, orbicules are found in igneous, metamorphic, or migmatitic rocks. The purpose of this study is to describe the occurrence of orbicular migmatites near Shoup, Idaho and to present and support a model for their petrogenesis. The orbicules are spheroidal masses (3-15 cm. in diameter) with xenolithic cores surrounded by concentric alternating shells of plagioclase and biotite.

Previous descriptions of orbicular rocks associated with the Idaho batholith include accounts by Goodspeed (1942) and Nold (1972). The Buffalo Hump locality described by Goodspeed shows orbicules in a fine-grained, quartz-biotite schist. Those described by Nold occur near Graves Peak in the pegmatitic portion of a major granodiorite pluton (Figure 1).

Area of Study

The area covered by this study is centered near Shoup, Idaho which lies on the Salmon River, eighteen miles west of North Fork, Idaho (Figure 2). The terrain is characterized by high relief (3,300-6,000 ft.). Most of the

FIGURE 1



INDEX MAP

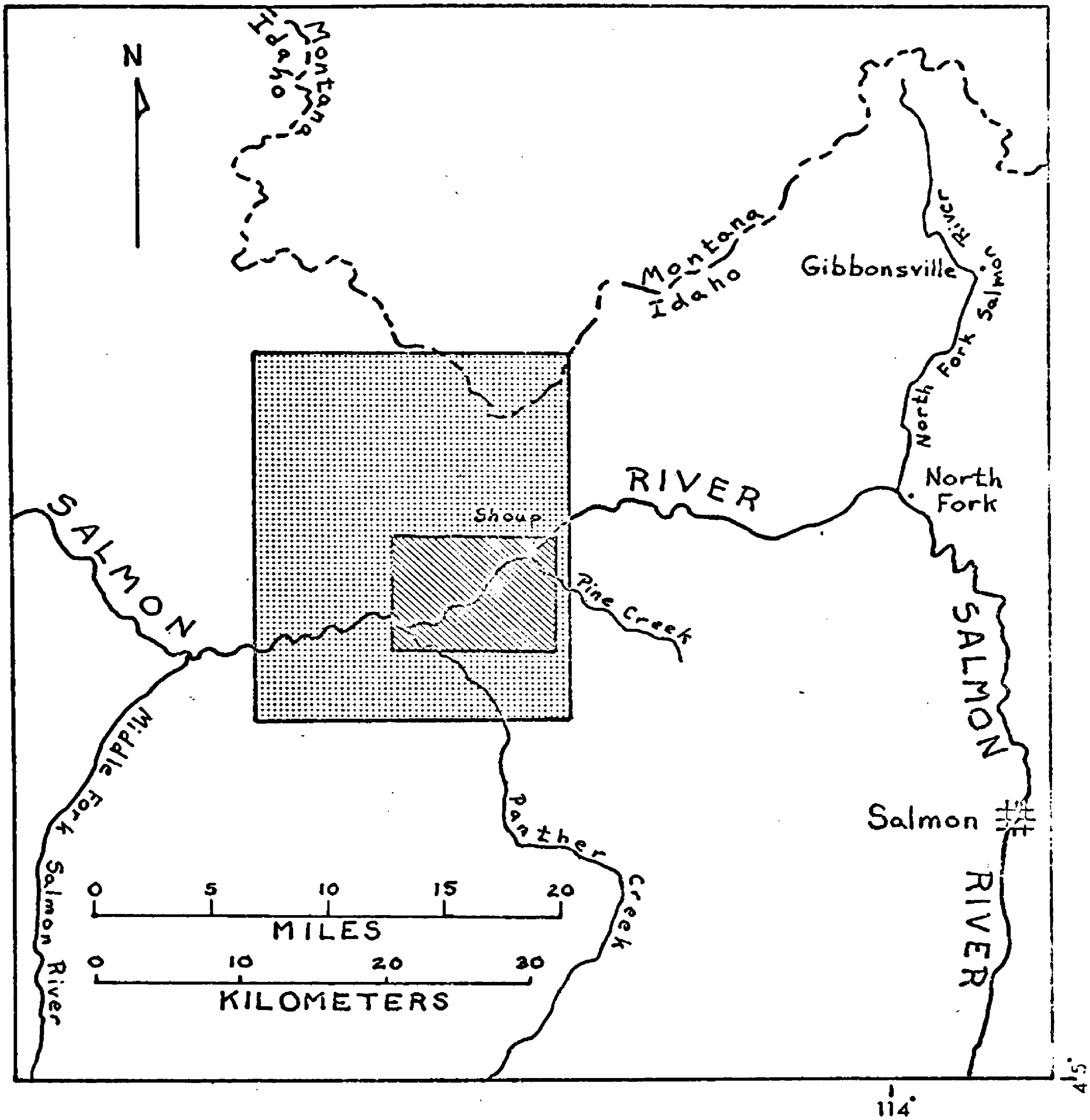
Idaho Batholith

Study Area

1 Goodspeed, 1942

2 Nold, 1972

FIGURE 2



INDEX MAP - SALMON RIVER REGION

Shoup Quadrangle

Study Area

research was conducted at the lower elevations where orbicular migmatites were exposed during widening of the Salmon River Road. The number of orbicule sampling localities was limited by extreme surface weathering of the rocks (Figure 3).

Regional Geologic Setting

The orbicular migmatites are situated in a geologically complex region. The dominant rocks are intrusives which may be related to the Idaho batholith. Massive granites and granite gneisses occur in the central portion of the study area and to the east of the area. The more complex migmatitic rocks are also found in the area's central portion.

Precambrian Belt Supergroup rocks are important in this region, outcropping south and east of the study area. The Belt rocks are predominantly quartzites and argillites which have been metamorphosed, in places, to phyllites, quartz-biotite-plagioclase schists, and gneisses.

Structural history and mineralization of this region are highly complex. Anderson, 1948, reports that forces involved during emplacement of the Idaho batholith have fractured the previously folded rocks aiding ore deposition for which the region is noted.

CHAPTER II

RESEARCH METHODS

Field

Field work involved detailed sketching of outcrops, photography and rock sampling. The vertical, unstable roadcut faces made photography and systematic sampling difficult. However, at localities I and II an attempt was made to sample for two vertical meters on fourteen meter centers (Figure 3). Sampling localities were recorded on a 1:62,500 topographic map of the Shoup Quadrangle.

Laboratory

Fifty-five samples were cut into slabs from which sixty thin sections were prepared. Each thin section slab was stained with sodium cobaltinitrite to aid the modal analyses. Larger slabs were cut in order to determine orbicule dimensions and to study orbiculite-migmatite relationships. Calcium content of plagioclase was determined by the oil immersion method (Appendix I).

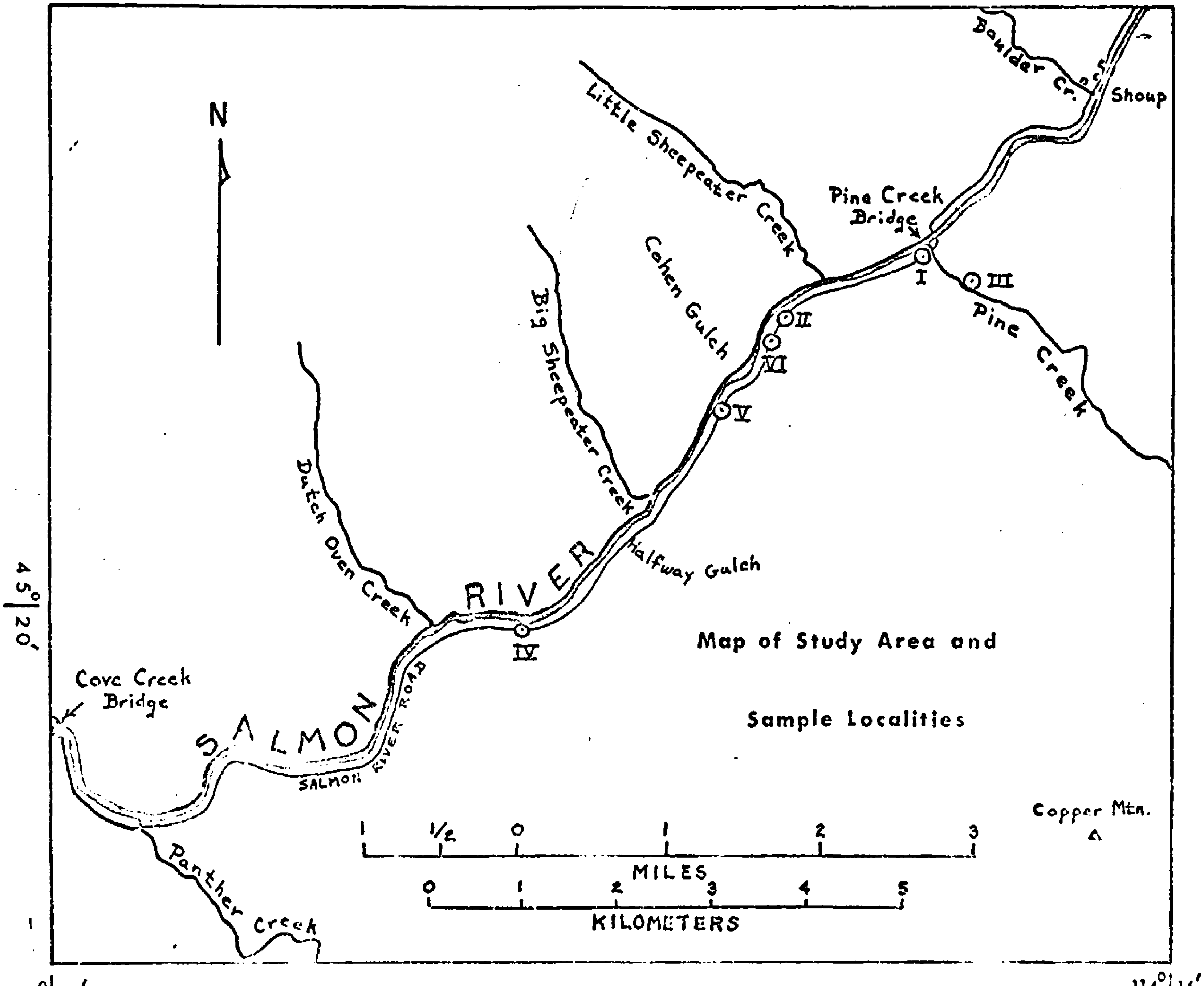

N
Boulder Cr.
Shoup
Little Sheepeater Creek
Pine Creek Bridge
Cohen Gulch
Big Sheepeater Creek
Pine Creek
I
II
III
IV
V
VI
Dutch Oven Creek
RIVER
SALMON
Halfway Gulch
Map of Study Area and
Sample Localities
Cove Creek Bridge
SALMON RIVER ROAD
Copper Mtn.
Panther Creek
1 1/2 0 1 2 3
MILES
0 1 2 3 4 5
KILOMETERS
45° 20′
114° 25′
114° 16′

FIGURE 3

CHAPTER III

FIELD RELATIONSHIPS

The study area shows an extreme diversity in rock types and associated structures. Several of these deserve attention here because they are spatially, if not genetically, associated with orbicules.

Igneous Rocks

The most abundant rock types within the study area are massive granites or granite gneisses. For reasons discussed below, these rocks will be called the "granite gneiss complex" (Figure 4). Separate units are not differentiated since the rocks appear to be homogeneous on a scale greater than 200 feet. Two very striking features of these rocks are the large microcline megacrysts and the strong foliation (Plate 1a). At several localities rocks of the granite-gneiss complex include xenoliths of plagioclase-biotite schist measuring 35-40 cm. in length. Flow foliation conforms to the outline of the xenoliths and each is surrounded by a fairly distinct reaction halo. At other localites, microcline megacrysts are porphyroblastic and metamorphic textures are prominent in thin section.

Dikes and veins of batholith-related tonalite

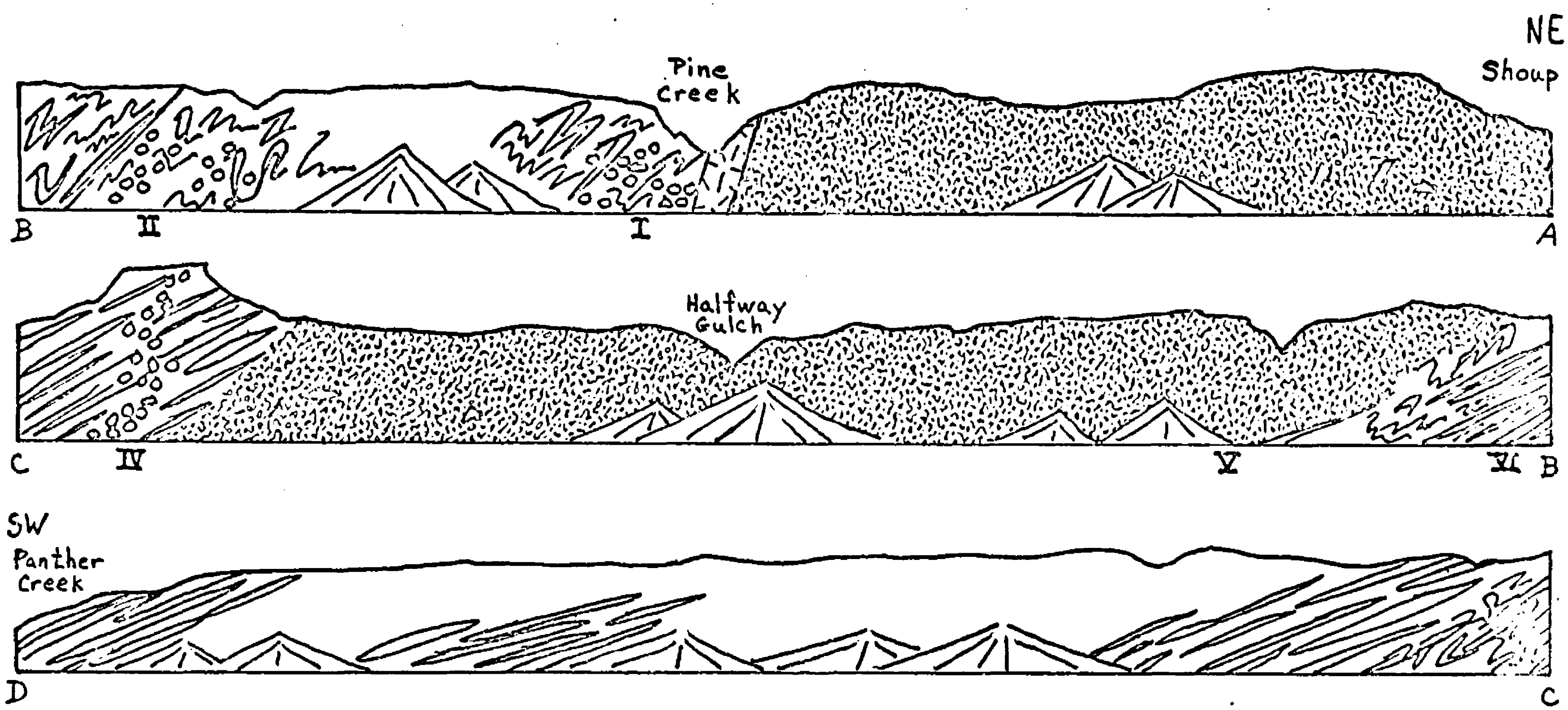
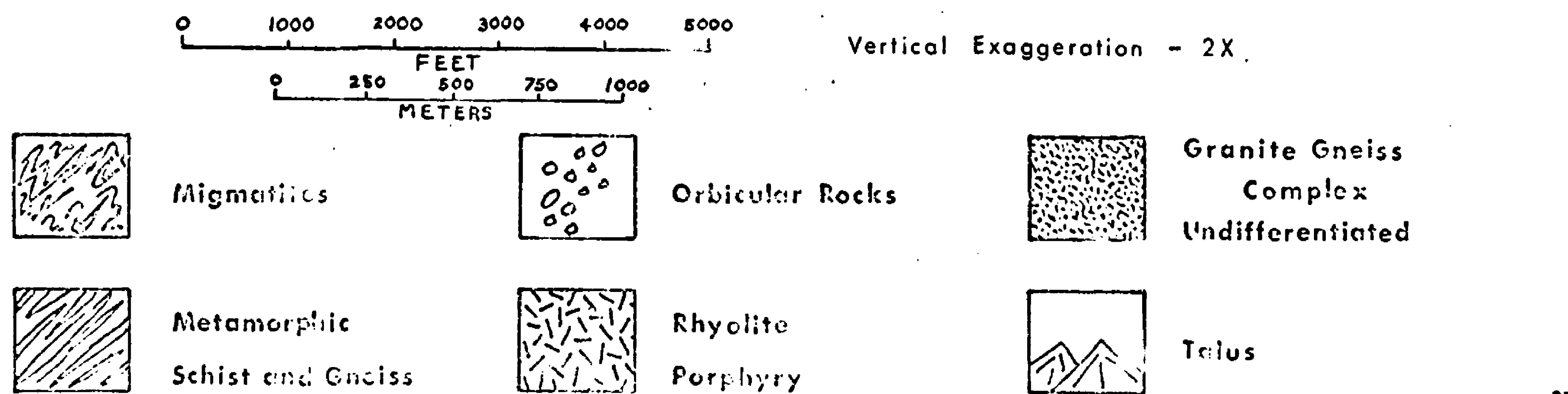


FIGURE 4

Schematic Geologic Cross Section, Shoup To Panther Creek



represent another major intrusive phase. Tonalite dikes attain a thickness of two meters or more, but are never as massive as rocks of the granite gneiss complex. This rock is characteristically white in color, of medium grain size, and commonly shows a faint foliation. Many tonalite dikes are zoned and carry schistose xenoliths such as that shown by sample I47b (Plate 1c).

Numerous, small pegmatite dikes and veins add to the complexity of each outcrop. These granite pegmatites exhibit a simple mineralogy, generally quartz, microcline and plagioclase with minor amounts of biotite and muscovite; no pegmatites with complex mineralogy were observed. The veins are generally sinuous and may cut across or parallel the foliation. Many of the pegmatites are zoned with quartz enriched toward the core and plagioclase and microcline enriched toward the wallrock; plagioclase is in many cases oriented (by shape) perpendicular to the wallrock margin.

One minor intrusion of grayish rhyolite porphyry forms the eastern boundary of locality I. The rock is very fine-grained and, in places, is heavily weathered to a dark reddish-brown color. Phenocrysts are predominantly plagioclase and quartz, and the groundmass is rich in alkali feldspar.

Migmatites

Migmatitic rocks are the dominant rock type from

Pine Creek west to locality V. Migmatite bodies are not confined to the area delineated by Figure 3. This area does, however, encompass all migmatites in the region which are known to contain orbicules.

All typical migmatite penetration structures are found within the study area. The following discussion deals with four prevalent penetration structures: layered (stromatic), augen (opthalmitic), schlieren, and nebulitic structures. Note that the migmatite nomenclature and interpretation used here follows that suggested by K.R. Mehnert, 1968.

Layered (Stromatic) structure. In several outcrops, a migmatitic rock (neosome) displaying light and dark layers has evolved from the parent rock (paleosome). The new migmatitic layers thicken and thin unevenly, parallel to the plane of schistosity: typical stromatic structure (Plate 4a). Quartz, plagioclase, and microcline form the hypautomorphic light layers (leucosomes) and biotite and plagioclase form the schistose dark layers (melanosomes). The light layers are tabular and isolated in three dimensions. This indicates that light layers were expelled from the parent rock under anatectic conditions. The layered migmatites do not evidence splitting of the schistosity planes by injection of magma, except where light layers join distinctly magmatic veinlets.

Augen structure. Augen structures discussed here are developed within the migmatite zones and do not include the regional augen-gneisses. Migmatitic augen are small feldspar eyes, one to two cm. in length. The augen-rich layers commonly occur parallel to or as lenses within layered or schlieren structures (Plate 4b). This indicates that augen are porphyroblasts which have grown from the parent rock.

Schlieren structure. Schlieren structures are the abundant penetration structures in the migmatites. Mehnert, 1968, suggests that schlieren may arise from previous migmatite structures by development of a pronounced flow foliation. At the Pine Creek and Little Sheepeater Creek localities, flow foliation is well developed. Here, the schlieren are sinuous, tapered, and often deflected by more competent inclusions such as orbicules (Plate 4c). These fabrics attest to the high mechanical mobility of the migmatite. In several places, the schlieren have been stretched out into even, nearly-parallel layers. The new migmatitic bands are ten to twenty cm. thick and should not be confused with the smaller-scale layered structures described above.

Nebulitic structure. Where parent rock and new migmatite can no longer be distinguished, the rock begins to look "magmatic". This "nebulitic" structure represents, according to Mehnert, 1968, the final stage of migmatite evolution prior to genuine magmatic intrusion. Several nebulitic lenses are present, and are bounded by less complex penetration structures. The nebulite is a fine-grained, mildly-foliated, biotite-plagioclase-quartz rock spotted with larger anhedral plagioclase (Plate 4d).

Orbicular rocks are found with each of the migmatite structures mentioned above. The relationship of orbicular rocks to migmatite structures is discussed in Chapter VII.

Metamorphic Rocks

Non-migmatitic metamorphic rocks of this region include phyllites, schists, gneisses and some hornfels. Near North Fork, the Belt Supergroup is metamorphosed to greenschist facies phyllites and schists. Westward toward Indianola, the rocks appear to be amphibolite-grade gneisses which show considerable shearing. No transition or precise boundary exists between these gneisses and rocks in the study area to the west. Therefore, the possibility exists that some flow foliation in the granites may represent a metamorphic fabric equivalent to these eastern gneisses. A thick sequence of fine-grained schists and gneisses dominates the western portion of the study area (Figure 4). These metamorphic rocks may be correlative with the Belt Supergroup.

Chronology of events

Rock structures define a relative sequence of events. Migmatite development appears to be first, followed by emplacement of the massive granite gneiss complex. Tonalite dikes invariably intrude the migmatites and rocks of the granite gneiss complex and are cut, in turn, by the pegmatites and aplites.

The geochronology here is expressed in relative terms. All the rocks in this area (excluding the Belt Supergroup) are considered to be late Cretaceous or early Tertiary in age. However, recent geochronologic work by R.L. Armstrong has provided 1.4 billion year dates on augen-gneisses on Panther Creek, and granites near Indianola. Therefore, the age of the igneous and metamorphic rocks in the study area may be pre-Belt and the migmatites and orbicular rocks may be unrelated to the Idaho batholith.

FIGURE 5

Cross Section – Locality 1

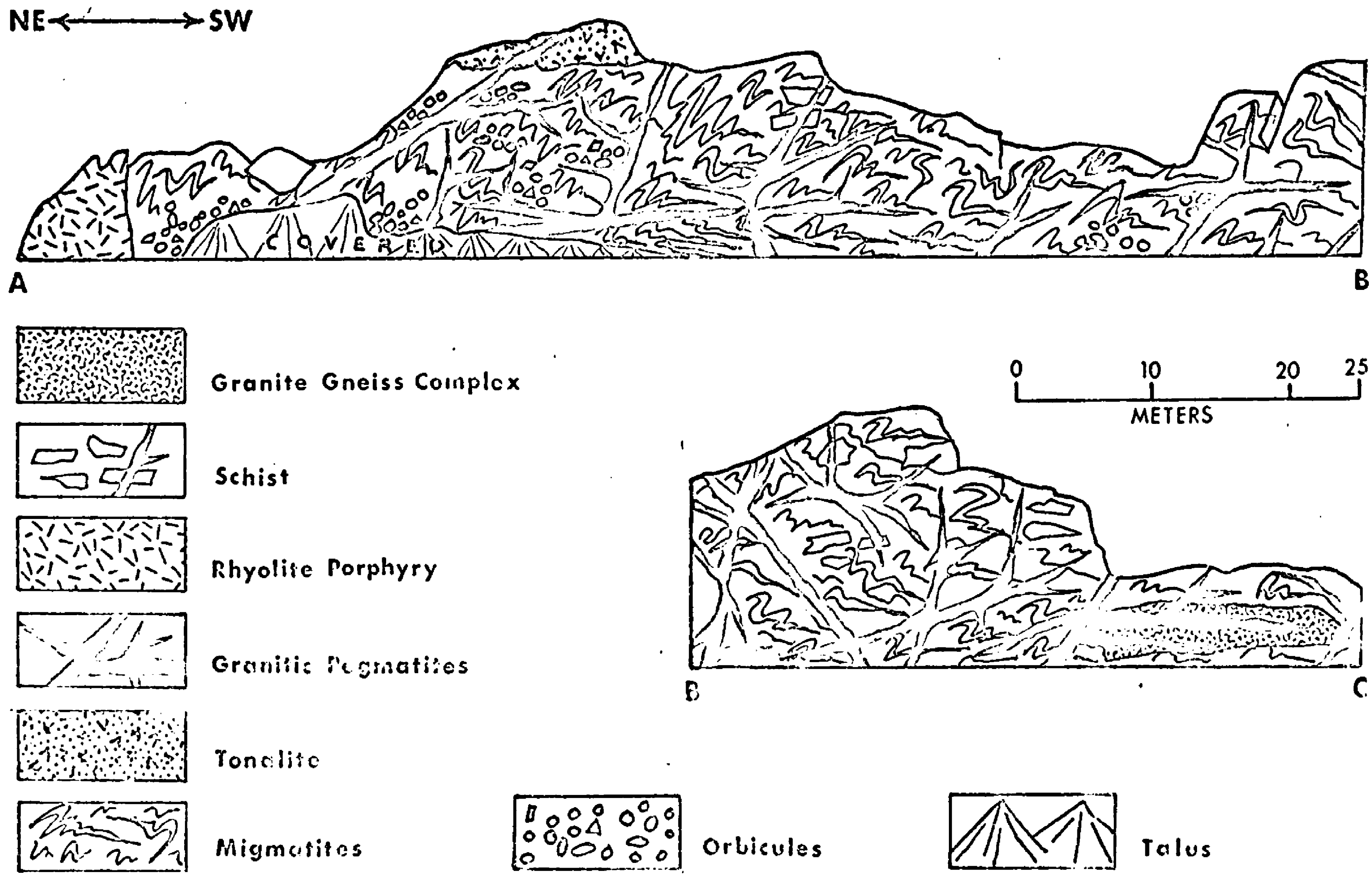


FIGURE 6

Cross Section – Locality II

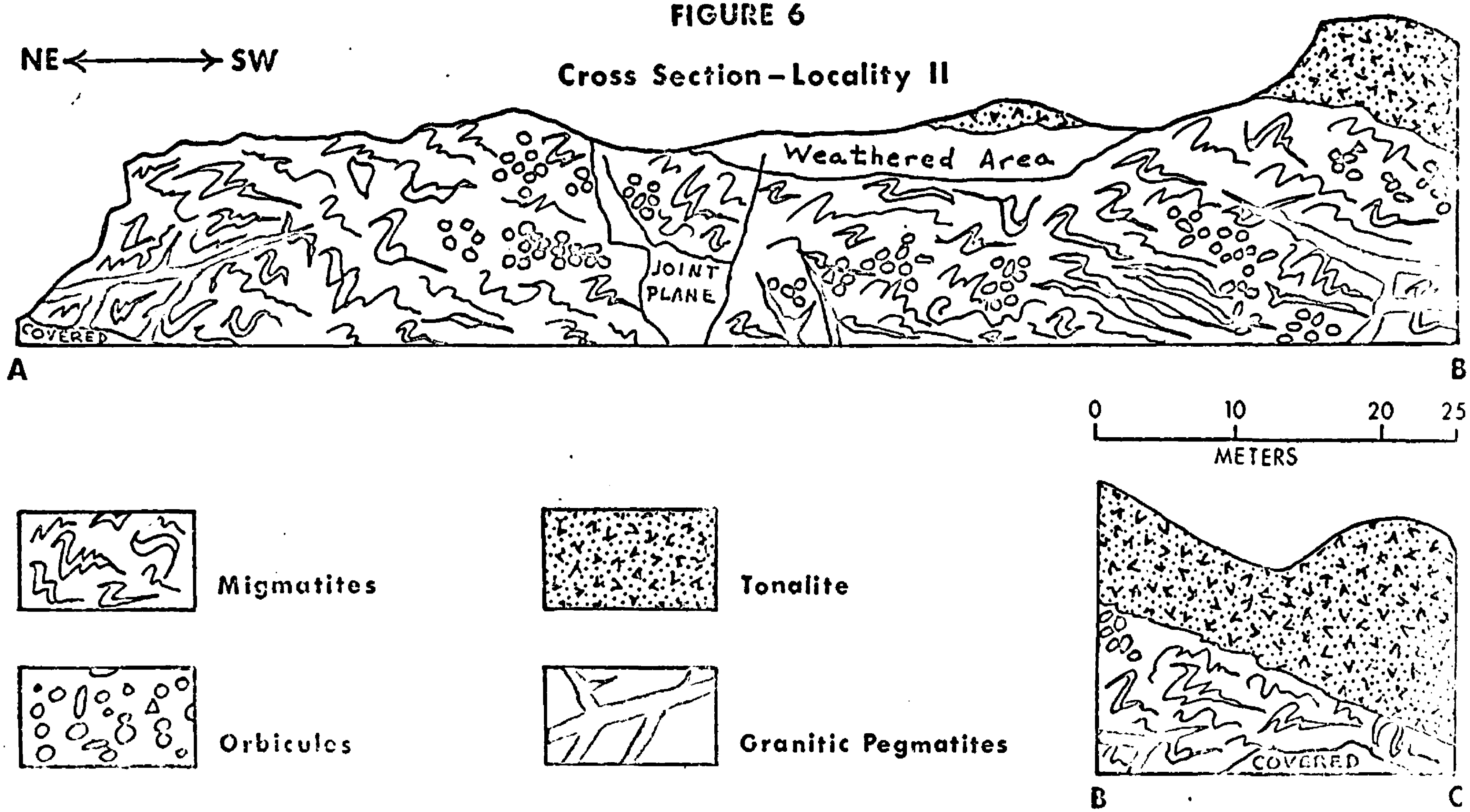
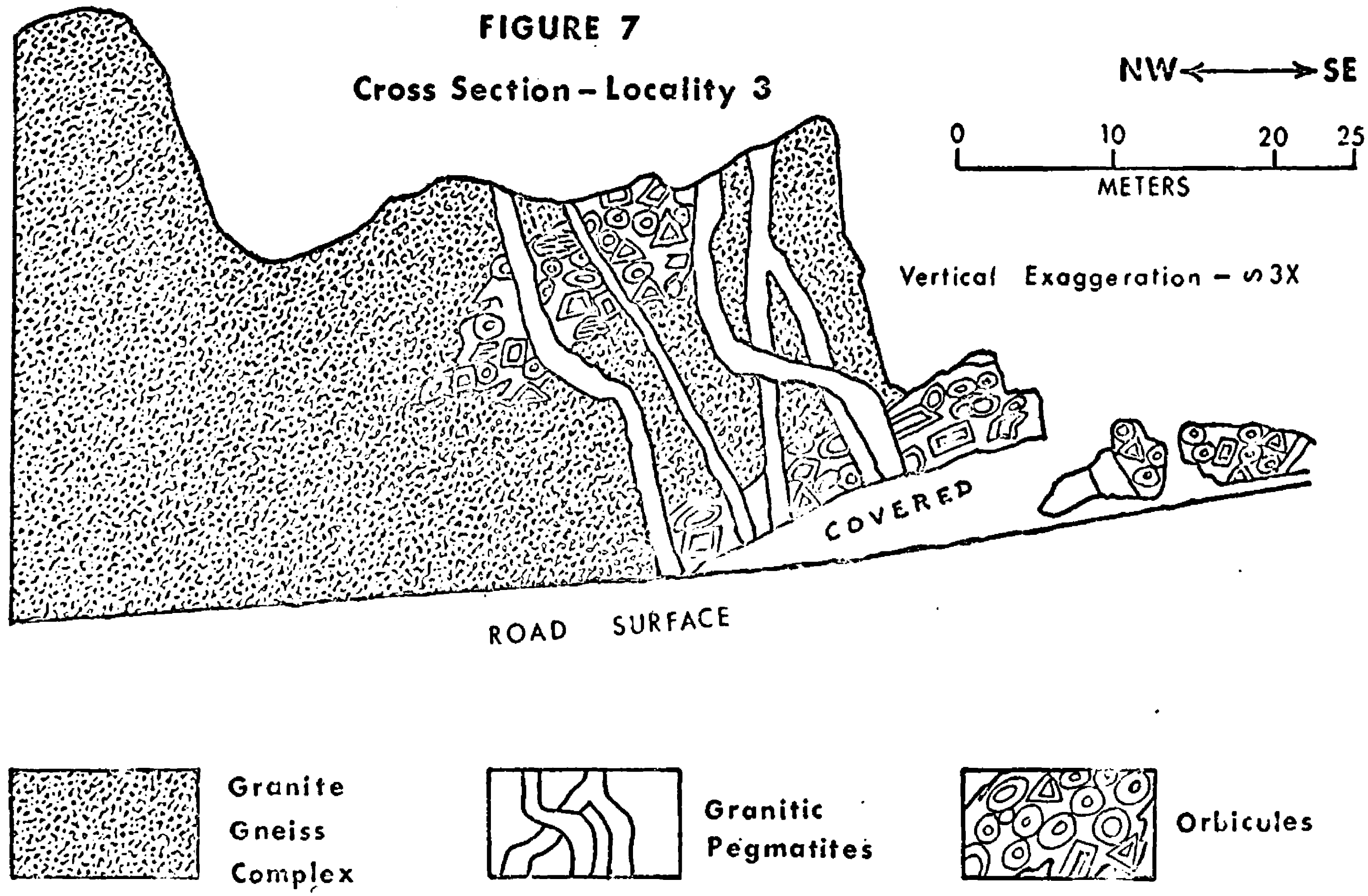


FIGURE 7

Cross Section – Locality 3



CHAPTER IV

PETROGRAPHY

This chapter discusses the thin-section textures and optical properties of minerals observed. It also considers macrostructures and thin-section textures of orbicules. A summary of optical properties of the minerals is in Table 1.

Mineralogy

Plagioclase. Plagioclase is the most abundant mineral within the migmatites, present in every sample collected for this study. Data in the Appendix show that refractive index determinations of calcium content of migmatitic and megacrystic plagioclase give values ranging from An 27 to An 31 (oligoclase-andesine).

In most of the samples examined, matrix plagioclases are of constant grain size and are subhedral to anhedral in outline. Very few thin sections show unaltered, euhedral plagioclase; sericitic alteration parallel to the twinning planes is common. Plagioclase also occurs as porphyroblasts, phenocrysts, and radiating prismatic crystals in orbicules (Figure 8).

Zoned grains of plagioclase are common (Plate 3a). Although zoning is weak, these crystals are easily

TABLE 1

MINERAL	SHAPE	SIZE (MM)	RELIEF	MISCELLANEOUS	ZONING AND PLEOCHR.
PLAGIOCLASE	eu - an	0.25-10.0	(+) ≃ qtz	heavily sericitized, large laths in orbs, An content 28-31	normal + oscillatory zoning
MICROCLINE	eu-an	0.05-50.0	very low	plaid twinning, megacrysts	
ORTHOCLASE	an	0.05-3.0	very low	minor constituent, space filler	
BIOTITE	eu-sub	0.05-5.0	mod. high	∥ extinction, nearly uniaxial, poikilitic in orb cores	z: dk brn-grn x: tan- lt brn
MUSCOVITE	eu-an	0.25-2.0	mod.	usually colorless, high birefringence	z: lt pink x: white
CHLORITE	eu-an	0.25-1.0	mod.	mauve + brown in x nicols, replacement	z: green x: yellow
HORNBLENDE	eu-sub	0.5-10.0	high	60°-120° cleavage	z: olive grn x: brown
QUARTZ	sub-an	0.25-20.0	sl. (+) ≃ plag.	commonly undulose, uniaxial (+), patchy	
SPHENE	eu-an	0.1-1.0	high	poikilitic, ◇ cross sections	? slight brown tint
APATITE	eu	0.05-0.1	high	low birefringence, uniaxial (-)	
CARBONATE	an	0.5-1.0	highly variable	high birefringence as space filler	
ZIRCON	eu	0.05-0.1	high	reaction halos in biotites	
GARNET	an	2.0-3.0	high	many inclusions, rimmed by muscovite	
MAGNETITE	sub-an	0.1-2.0	high	gray-silver in reflected light	
PYRITE	an	0.1-2.0	high	brassy yellow in reflected light	

FIGURE 8

Sample 13a - magnified 30X showing large plagioclase laths (P) radiating from the biotite-rich core of a thin-shelled orbicule. Quartz (Q) appears as a space filler between altered plagioclase laths; M=muscovite, B=biotite.

recognized by their highly sericitized cores, and by the change in extinction position from core outward. In sample II29, alteration of plagioclase cores is so pronounced that it gives a sugary appearance to the hand specimen. Heavy alteration of cores suggest that they are more calcic than the rims, a deduction directly verified by two An determinations on grains in sample II29a. Grain rims give An-32 values; higher extinction angles in the core indicate higher An in the cores. Grains with oscillatory zoning were also observed.

Plagioclase twinning is abundant and readily identifies the mineral in thin section. Twins present include albite, carlsbad, pericline, and carlsbad-albite twins. Carlsbad and carlsbad-albite twins are suggestive of igneous origin (Subramaniam, 1956; Jens, 1972); both of these twin types are prevalent in orbicule shells and in the orbicule matrix. Similarly, many plagioclase laths in orbicules exhibit a "segmented" twinning which indicates that these are recrystallized grains of igneous parentage. A few deformation twins occur in orbicule samples SR3 and SR12b, but none are present in the migmatites.

Alkali Feldspars. Microcline is the most abundant alkali feldspar, followed by orthoclase; no sanidine was observed. These feldspars occur within the tonalites, granites, granitic pegmatites and aplites, and augen gneisses. The grains are commonly subhedral to anhedral and occur in the matrix or as phenocrysts, porphyroblasts, or fracture fillings.

Several features are characteristic of the alkali feldspars in thin section. Microcline is readily distinguished from orthoclase by its plaid twins. Where orthoclase is present, it shows pronounced carlsbad twinning. In the intrusive samples and augen gneisses, myrmekitic features are common and may evidence two generations of development (Plate 3b). Microperthites are also prevalent and may embody an entire grain or a small portion within a grain.

No alkali feldspar is found within the migmatites except where it has been introduced by intrusions. It is possible that alkali feldspar was removed from the parent rock by anatexis or metamorphic differentiation. In either case, however, some microcline or orthoclase should occur with quartz and plagioclase in the lighter migmatitic layers. Its absence suggests that little or no alkali feldspar was present in the parent rocks.

<u>Quartz</u>. Quartz is present in every thin section and constitutes as much as 38%, by volume, of the sample. Quartz grains in the intrusive rocks and migmatites are characteristically anhedral with interlocking boundaries. Euhedral to subhedral phenocrysts occur in the rhyolite porphyry.

In the migmatite gneisses, quartz is distinguished from untwinned plagioclase by undulose extinction, uniaxial positive figures, and lack of alteration. In the darker migmatitic layers, quartz, plagioclase and micas develop a granoblastic-polygonal texture. Dimensional orientation of quartz parallel to the schistosity is obvious in several thin sections; ribbon structure is weakly developed in the more highly deformed rocks.

Quartz also serves as a space filling. This is very apparent in the orbicules where quartz fills spaces between plagioclase laths (Plate 3c).

Micas. Biotite is ubiquitous in the migmatites and is invariably present in thin section. Grains are euhedral to subhedral, and highly pleochroic. Alteration of biotite to chlorite is common, especially in the orbicule shells, where it is nearly complete.

Biotite defines the migmatite schistosity and magmatic flow foliations and in several thin sections constitutes a strongly recrystallized crenulation (polygonal arcs). The mineral also forms mafic border selvages adjacent to some magmatic and anatectic veins (Plate 1b and 1d).

Muscovite coexists with biotite as clear to slightly pleochroic euhedral grains. Muscovite also occurs as a fine-grained sericitic alteration of plagioclase and as larger anhedral replacement grains. In several thin sections, muscovites are deformed and show a wavy extinction; some of these grains have strongly embayed outlines.

<u>Opaque minerals and Garnet</u>. Magnetite is present in most thin sections as fine-grained subhedral grains. Lack of skeletal, tabular outlines and leucoxene coatings helps to distinguish magnetite from ilmenite. Pyrite was identified in several thin sections by its pale brassy yellow color in reflected light. Pyrite has been introduced along fractures and is heavily altered to a deep red hematite. One garnet grain occurs in sample SR12b; it is highly fractured and is partially rimmed by fine-grained muscovite.

<u>Accessory Minerals</u>. Amphibole is abundant in samples from locality V but is otherwise confined to a few dark, migmatitic layers. In sample V4, hornblende occurs as small, euhedral grains and as large anhedral phenocrysts rimmed by tangentially-oriented biotite (see Table 1 and Plate 2b). Carbonate completely replaces the fine-grained amphiboles of an orbicule core in sample I59 (Plate 3d). Apatite is almost ubiquitous as small, round, matrix grains. Sphene and zircon appear in several thin sections; biotite commonly includes zircons surrounded by distinct reaction halos.

CHAPTER V

ORBICULE STRUCTURE

Classification

Three distinctly different orbicule types occur within the study area. Orbicules are classified here in a manner similar to that suggested by Leveson, 1963; orbicule type is a function of the number of shells and the mineralogy and structure of the core of the orbicule.

Thin-Shelled Orbicules. All xenolithic fragments which are rimmed by one layer of plagioclase are designated "thin-shelled orbicules" (Plate 5b). The plagioclase grains commonly show dimensional orientation with their long axes perpendicular to the core boundary. The orbicule size varies from two to twenty cm., measured on the longest dimension. Orbicules with megacrystic cores represent a slightly different orbicule type but they will be classified with thin-shelled orbicules (Plate 6a).

Orbicule shapes reflect the shape of their cores; this is especially apparent in thin-shelled orbicules (Plate 5a). Most orbicules are spheroidal or ellipsoidal because their shells have conformed to rounded nuclei; xenoliths within a mobile magma are readily rounded by abrasion. In contrast, thin-shelled orbs at locality VI are characterized by tabular or lenticular xenoliths with thin, discontinuous plagioclase rims. At locality III, xenolithic fragments are very angular and therefore, the resulting orbicules are angular.

<u>Composite Orbicules</u>. Orbicules with two or three shells of contrasting mineralogy are considered composite orbicules; this is the most abundant orbicule type (Plate 5c). The additional shell is usually randomly oriented biotite or fine-grained magnetite. Composite orbicules are more ellipsoidal in outline than thin-shelled orbicules and have a size range of three to ten cm.; the mean diameter is five cm. The long axes of the ellipsoids commonly lie in a plane parallel to the migmatite schistosity. Composite orbs form on cores of varying composition.

<u>Multiple-shelled Orbicules</u>. Multiple-shelled orbicules are identified by their numerous, alternating light and dark shells (Plate 5d). The average number of shells in multiple-shelled orbicules is eight (see Appendix), and two orbicules show eleven separate shells. Shell spacing is highly variable and in most cases, shells are discontinuous or non-concentric. Only one orbicule examined showed a systematic shell spacing (approximately one cm. intervals). Orbicules from a single locality have a variable number of shells. Multiple orbicules commonly have an outer-most shell of fine-grained, equidimensional.

quartz and feldspar.

Core Types

Several rock types on which orbicules nucleate have been identified (Plates 5 and 6). Schistose cores are the most common type. Cores of biotite-rich schist occur in every locality and are expecially prevalent in multiple-shelled orbicules; in several, the cores are almost wholly biotite. Several orbs have nucleated on slender fragments of muscovite-rich schist. Schistosity in these fragments is in some cases preserved depending on the degree of recrystallization during orbicule growth.

Thin-shelled orbicules with cores of tan to pink quartzite were found at locality I. In these, the core-rim boundary is marked by disseminated, fine-grained magnetite. An orbicule in sample II55 has nucleated on a large fragment from a previous orbicule (Plate 6c). In samples IV5 and IV6, crystals of plagioclase and microcline serve to nucleate thin-shelled orbicules (Plate 6a).

Most orbicule cores are correlative with nearby "country rocks". Quartzite core fragments at locality I were probably derived from a sedimentary orthoquartzite wallrock. Although this wall rock was not located, a thick tan to pink quartzite layer at locality VI bears a striking resemblance to the orbicule cores. Similarly, cores of hornblende-biotite-plagioclase schist, abundant at locality II, are compositionally and texturally correlative with migmatitic layers at locality V. Many thin-shelled orbicules develop on schistose fragments wedged away from the directly adjacent migmatite layers.

A few additional orbicule structures deserve mention. Orbicules commonly project into the schistose migmatite layers (Plate 6a); in these cases, the foliation wraps around the orbicules. Orbicules are commonly crowded together (Plate 4b). Some authors suggest that mutual interference of orbs during crowding determines orbicule shape (Leveson, 1963, Grip and Russell, 1971). Evidence considered in Chapter VI indicates that these orbs were more rigid bodies and that orbicule shape was controlled solely by shape of the cores. No evidence suggests that the size or complexity of an orbicule is controlled by the type of core.

CHAPTER VI

ORBICULE GENESIS

Various petrologic problems encountered in this study are discussed below. They are:

A) the geologic environment(s) which effected the growth of orbicules

B) the geologic environment which effected crystallization of the orbicule matrix

C) elastic properties of the orbicules

D) the physical, chemical, and chronological relations between orbicular rocks and the associated migmatites

Igneous Origin

Several lines of evidence support an igneous origin for the individual orbicules. Orbicule cores offer the most convincing data for this origin. Cores of schist and quartzite represent wallrock fragments which appear to have been incorporated into a magmatic body and have subsequently served to nucleate shells of plagioclase and biotite. Quartzites and muscovite schists bear no textural or mineralogical relationship to nearby country rock and therefore, must have been rafted in from another region by igneous magmas.

Monomineralic orbicule cores also argue for an igneous origin. Vance (1966) notes that the active attachment of crystals suspended in a melt, synneusis, can develop a distinctive magmatic fabric. Like minerals will preferentially unite in twinned or dimensionally-parallel orientation during turbulent magmatic episodes. At locality II, several orbicules with monomineralic cores were identified. The author suggests here that synneusis produced at least the initial attachment of biotite plates, and may have been responsible for aggregation of the entire biotite core. At the center of these cores, synneusis is indicated by the parallel crystallographic orientation of several biotite grains (Figure 10). Randomly-oriented biotites are more prevalent in the outer core regions.

A quantitative examination of orbicule shell spacing (Appendix) indicates that the interval between successive shells varies irregularly. This pattern has been attributed to igneous crystallization (Leveson, 1963); orbicule growth progresses at an irregular rate due to fluctuation in external conditions. Metamorphic processes involve more stable physico-chemical conditions and therefore would generate orbicules with shell spacing in exponential progression (Leveson, 1963).

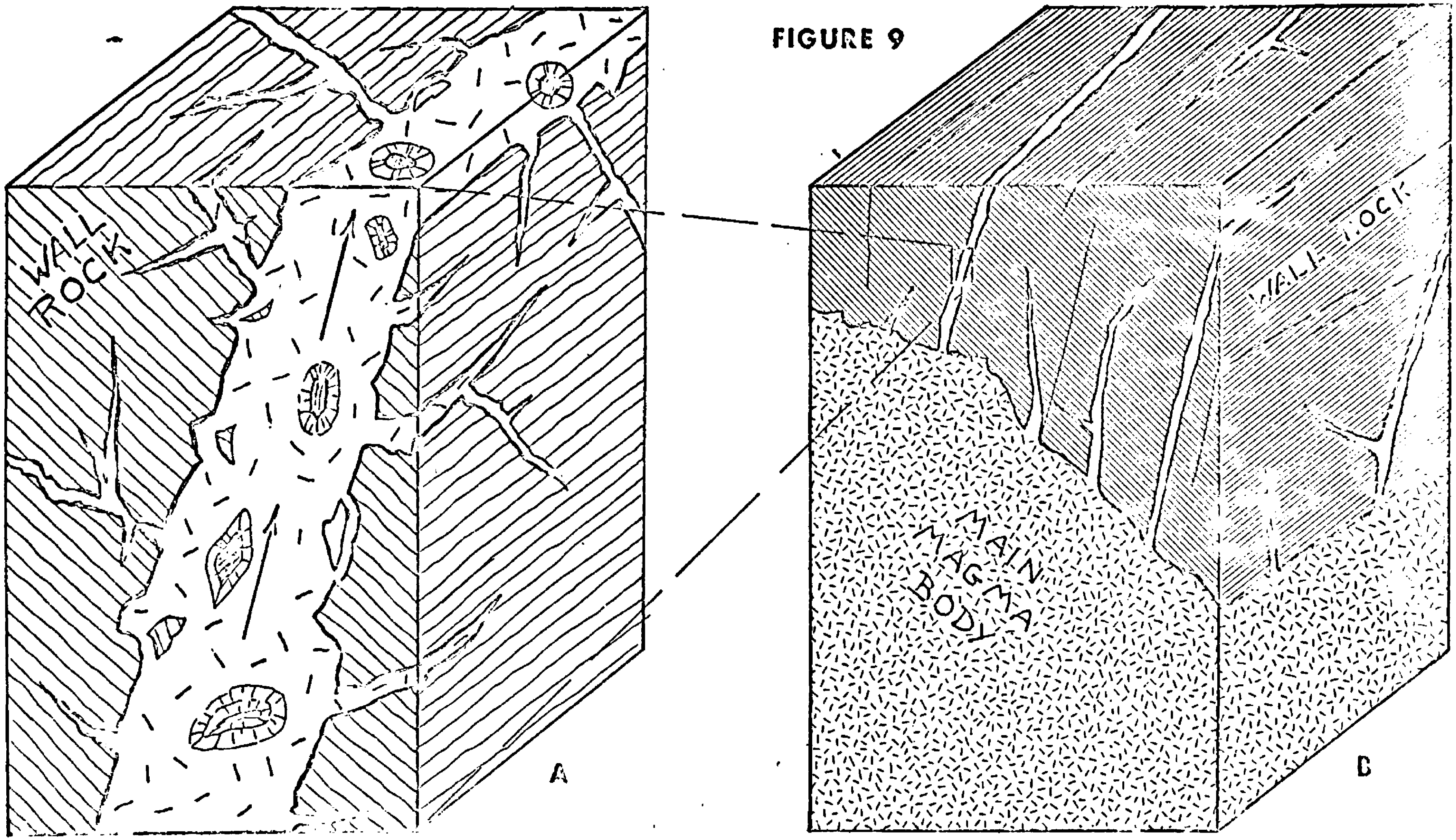
Proposed Model of Crystallization

An intrusive igneous body was apparently responsible for the formation of orbicules. Orbicules crystallized on xenolithic fragments within dikes of supercritical aqueous fluid (possibly a pegmatite, Figure 9A). These dikes may have connected with a larger plutonic body deeper in the crust (Figure 9B). This aqueous fluid streamed upward at high velocities, had a moderate to low viscosity, and contained at least some suspended crystals. These conditions are neccessary to explain the suspension, crystallization, upward movement, and subsequent abrasion of relatively dense orbicules. This model is similar to one suggested by Moore and Lockwood (1973). Discussion and evidence for this model are given below.

It is important to note here that the spatial and chronological dimensions of the above-mentioned pluton have not been delineated. A multiplicity of subsequent igneous events has eradicated any record of the pluton dimensions. Therefore, the orbicular rocks and migmatite may be associated with an early magmatic phase related to the Idaho batholith, or they may correlate with the much earlier pre-Belt dates secured by R.L. Armstrong, 1973.

Apparently two important chemical aspects characterized the upward-streaming supercritical aqueous fluid. First, the fluid was enriched with the components of biotite, quartz, and sodic plagioclase. Second, since adjacent shells show alternating compositions, physico-chemical factors controlling orbicule crystallization must have been variable. This variability at the crystallization site can

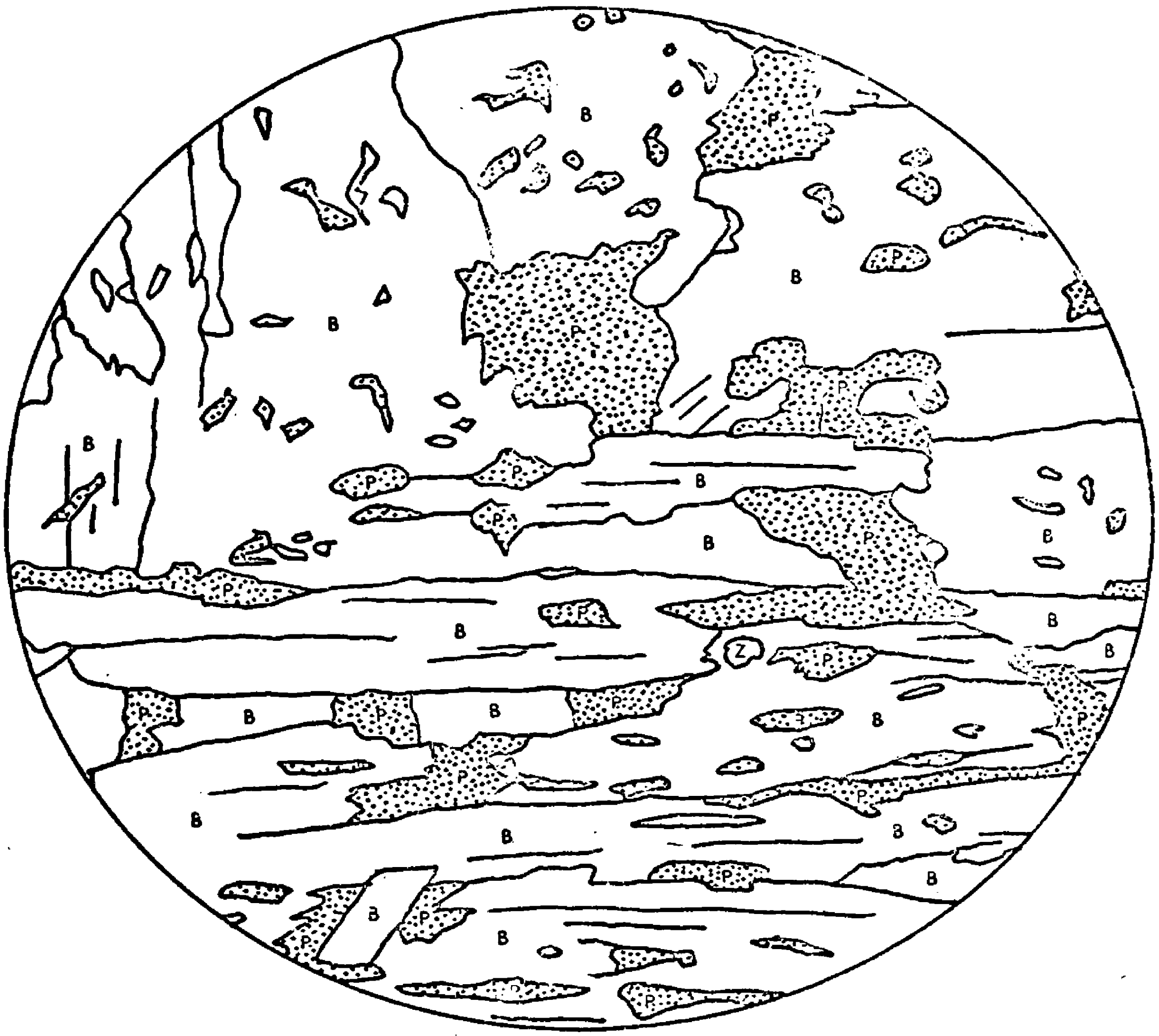
FIGURE 9



A. Schematic cross section through the wall rock showing the intruding supercritical aqueous fluid which is carrying orbicules.

B. Schematic cross section showing possible connection between the orbiculite dikes and a large plutonic body at depth.

FIGURE 10



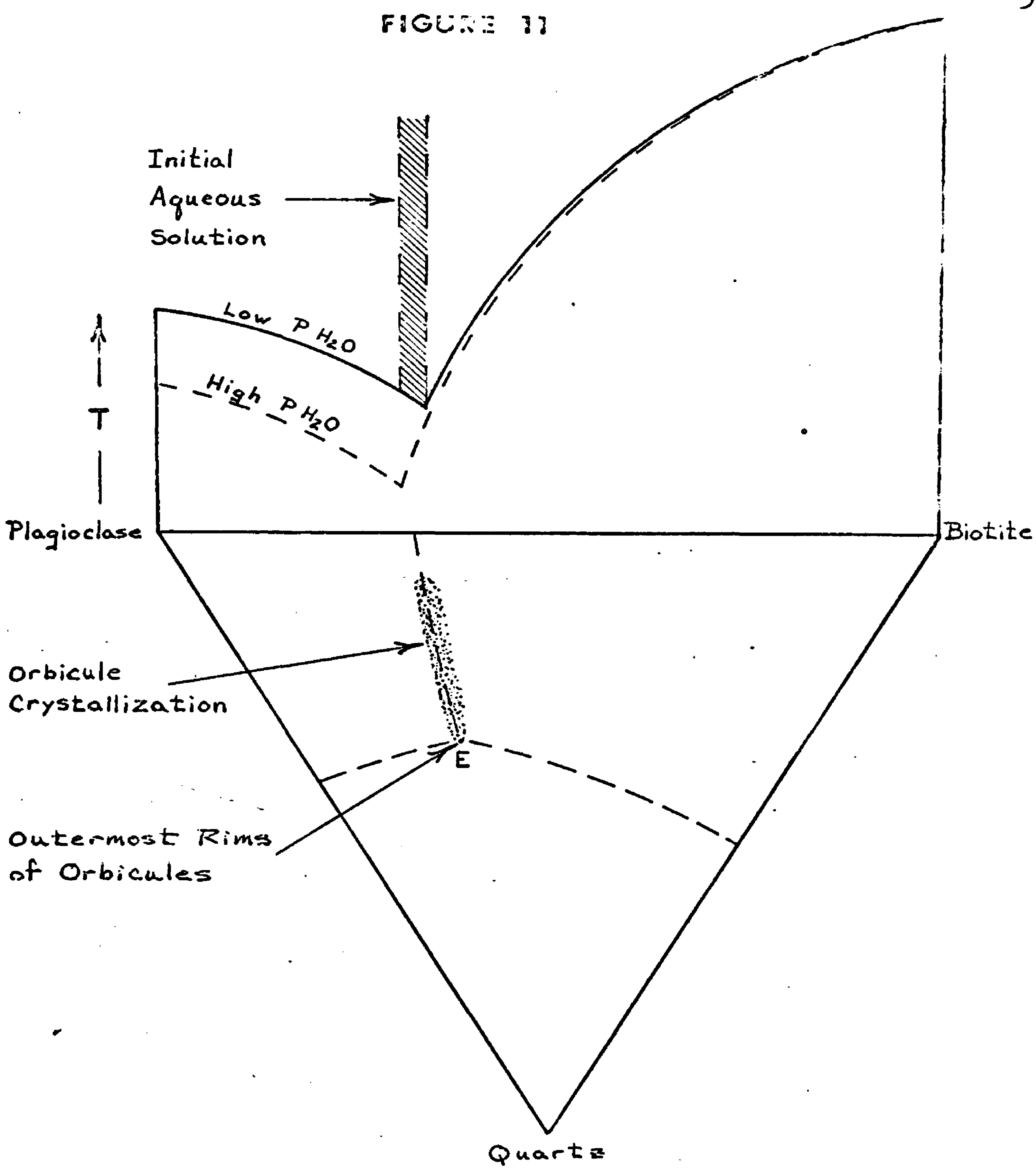
Sample II2 - magnified 30X to show the contrast between synneusis texture and random grain arrangement in the shell of an orbicule. All biotites (B) in the lower half of the drawing have parallel crystallographic orientation. Plagioclase (P) and biotites in the upper half have attached to the core by random adherance; z=zircon.

be produced in three ways: 1) the activation or cessation of upward streaming could move orbicules into regions of contrasting composition, 2) the aqueous fluid originated within different water-saturated country rocks and therefore the fluid chemistry varied, or 3) fracturing the roof of the pluton changes the hydrostatic pressure. The fairly constant mineralogy of orbicule shells suggests that models 1 and 3 are more important here.

To illustrate the first model, the incorporation of a quartzite fragment triggers the crystallization of plagioclase. If the velocity of upward streaming exceeds the gravitational settling rate of the orbicule, the orbicule may move into a region where the fluid chemistry is such that biotite begins to crystallize. A cutoff of upward streaming would cause the orb to sink back into the horizon of active plagioclase crystallization. Regeneration of fluid streaming begins a new cycle. Thick shells of plagioclase may have crystallized as orbicules moved rapidly upward through a thick, homogeneous horizon, slowly through a thin horizon, or remained immobile within the H_2O-rich fluid. Thin shells crystallized in the opposite manner. A fluid of moderate to low viscosity would facilitate rapid rising and sinking of orbicules.

Orbicule crystallization is possibly best explained by model 3. The following discussion refers to Figure 11, a ternary diagram for the hypothetical system plagioclase-

FIGURE 11



Hypothetical ternary diagram for the system quartz-biotite-plagioclase: E is the ternary eutectic, and the stippled region indicates the area in which the crystallization path fluctuated.

biotite-quartz. The initial composition of the aqueous fluid probably varied within the shaded region; the components did not form solid solutions. During the time that orbicules remained within the mobile aqueous fluid, the path of crystallization fluctuated in a region adjacent to the plagioclase-biotite cotectic (stippled area). This is indicated by the absence of primary quartz from the inner orbicule shells. With a high P_{H_2O}, only plagioclase will crystallize. As fracturing of the overlying rock lowers the P_{H_2O}, the curve in Figure 11 is elevated and biotite and plagioclase crystallize simultaneously. As pressure again increases, the curve is depressed and only plagioclase crystallizes. The quartz-plagioclase outer shell which is common to multiple orbicules formed after crystallization proceeded to the ternary eutectic.

At Locality 4, orbicular quartz-diorite is exposed for two hundred vertical feet. The orbicules are thin-shelled, nearly spheroidal, and have nucleated on small biotite clusters or feldspar megacrysts. Orbicules here are crowded together; the presence of xenoliths and fragmented orbs indicates a highly mobile environment. The orbicular rocks were intruded concordant to and discordant to layers of metamorphic rocks. This exposure does not represent the parent fluid for orbicules farther east. However, it does show that orbicules in this region were actively transported by magmatic fluids.

Elastic Properties of Orbicules

A detailed study of the physical properties of orbicules was not attempted, but one observation deserves discussion. The orbicule matrix is commonly littered with fragments of orbicules (Plate 4b). These fragments, which range in size from one to eight cm., indicate that the orbicules were relatively brittle objects. Tightly crowded orbicules also support this conclusion. Orbicules do not deform plasticly during crowding but instead, fit together according to their existing shape. Figure 12 shows how tight packing of orbicules is affected by orb outline, and indirectly by core outline.

Migmatite Association

With the exception of Locality IV, orbicular rocks are found with migmatites. The orbicular matrix commonly shows a crude parallelism with respect to the migmatite layering or cuts directly across the layering. Some migmatite penetration structures such as schlieren blend into the margins of the orbicular rocks but never crosscut completely. At Locality II, schlieren layers wrap around a large multiple orbicule; a small amount of fragmental orb matrix is present (Plate 4c). Therefore, the emplacement of orbicular rocks seems to be contemporaneous with migmatite formation. Orbicules must have crystallized deep enough in the crust for contemporaneous development of migmatites. Some schlieren layers may have developed

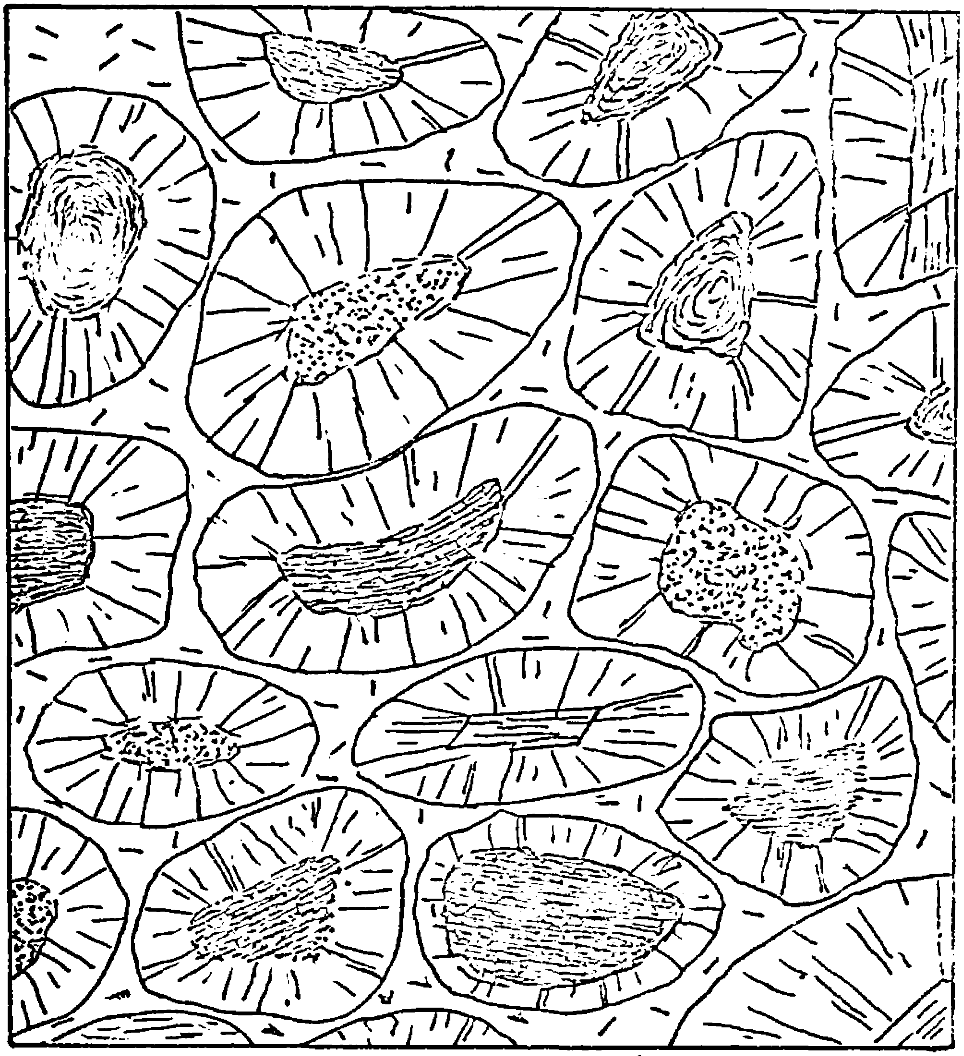


FIGURE 12

Drawing shows how orbicules from these localities did not deform during crowding, but instead fit together according to their shape (shape determined by core dimensions).

within the aqueous fluid, however there is no field or petrographic evidence for this possibility.

Alternative Mechanisms

D.J. Leveson (1966) has compiled several hypotheses of orbicule genesis which should be considered as alternatives to the model suggested above. They are:

1) Reactions between magma and xenoliths produce orbicules (Cole, 1916; Koide, 1951; Grip and Russell, 1971).
2) Orbicules crystallize by movement of nuclei through parts of magma of differing composition (Sederholm, 1928).
3) A nucleus promotes excessive plagioclase crystallization which supersaturates the surrounding magma in ferromagnesian components; the excessive crystallization of these components supersaturates the magma in plagioclase. The cycle repeats until the magma is depleted in both components (Iddings, 1909).
4) Orbicules are generated by active diffusion during granitization (Eskola, 1938) in a manner similar to formation of Liesegang rings in a gel (Ishioka, 1953; Leveson, 1963).
5) Orbicules may form under conditions produced during sodium metasomatism of mafic rocks. Na^{+1} ions are

diffusing inward, Ca^{+2}, Mg^{+2}, and Fe^{+2} ions diffuse outward (Simonen, 1950).

The mechanism suggested by 3 requires a relatively quiet environment; shells would be fairly concentric and the matrix would be free of fragmented orbicules. However, the textural evidence discussed in this paper suggests a mobile environment for orbicule development.

Another possibility is that orbicules grew by the methods suggested by 4 and 5. Although the orbicules commonly occur with migmatites, these mechanisms would have to account for the random shell spacing, the contrasting orbicule cores, angular cores, and the observed igneous textural relations.

Orbicule development by hypothesis (1) could be applicable to these rocks. However, xenoliths and xenolithic cores of orbicules do not evidence substantial reaction with the magma; they seem to have served only as nucleation surfaces for other minerals.

CHAPTER VII

POST-ORBICULE EVENTS

The intrusion of granitic pegmatites and aplites seems to be the most important factor in post-orbicule deformation. Pegmatite veinlets commonly penetrate the orbicules as shown in Plate 5b. In some cases, orbicules have been split and/or enlarged by pegmatite veins. The multiple-shelled orbicule shown in Plate 6c has been fractured by an intruding vein; in other multiple-shelled orbs, shells have been spread apart by the veinlets. Only a few quartz-plagioclase anatectic veinlets have penetrated the orbicules.

Large fractures in several of the orbicules studied are evidence for structural deformation after orbicule formation (Plates 5d and 6b). Fracturing was accompanied by the influx of hydrothermal solutions. In thin section, the fractures are rich in pyrite and chlorite; plagioclase laths adjacent to the fractures are heavily sericitized. Fluids introduced along the joint plane indicated in Figure 6 have severely altered the plagioclase and hornblende in orbicules which are cut by the fracture.

It is possible that some orbicules were deformed during a remobilization of the migmatites. However, with the exception of the cross-cutting anatectic veins mentioned above, no field or petrographic relations appear to substantiate this idea.

CHAPTER VIII

CONCLUSIONS

Reviewing the evidence brought forth by this study, a primary conclusion is that the orbicules crystallized in an intrusive igneous environment. Many orbicule cores are apparently xenolithic fragments. The cores do not correlate with the adjacent migmatites but may correlate with other metamorphic rocks in the study area. Abrasion and fragmentation of orbicule shells suggest that orbs were highly mobile during crystallization and behaved as rigid ellipsoids.

Structures and textures observed in the field suggest that orbiculite intrusion was contemporaneous with migmatite development. Since migmatites do not form a single mapable unit, it is difficult to define their relation, if any, to a pluton or plutons.

The number of orbicule localities discovered during this study indicates that orbicular structures adjacent to the Idaho batholith may be more common than previously imagined. Future research in the form of geochronologic and structural surveys may delineate the pluton(s) responsible for orbicule and migmatite development.

Plate 1a - Sample I 18 with microcline megacrysts and striking foliation of rocks in the "granite gneiss complex". Granitic pegmatite cuts across the foliation.

Plate 1b - Sample VI 3 showing an anatectic, granitic pegmatite parallel to migmatite layers. Biotite forms the border selvage, and microcline is prevalent in the lighter-colored pods. Note how migmatite schistosity conforms to the vein dimensions.

Plate 1c - Tonalite, sample I47b, showing mild foliation and zoning of the vein (righthand side of photograph). The biotite-plagioclase xenolith at the center of the vein shows a faint reaction halo.

Plate 1d - Sample VI 5 from a thick quartz-rich layer in the layered migmatites. Intruding tonalite has developed a slight mafic selvage of fine-grained magnetite. Note faint cross-dike foliation.

Plate 1

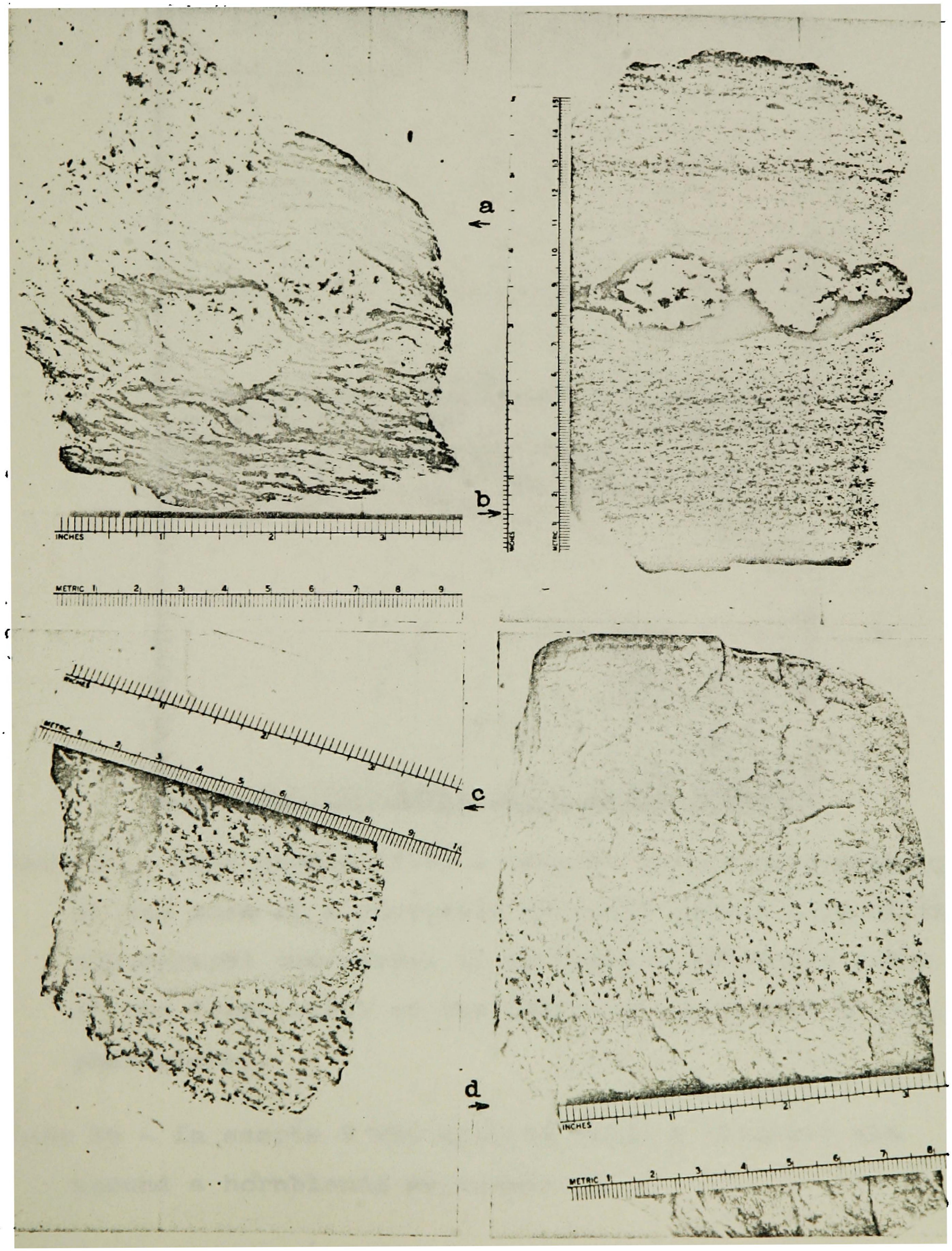
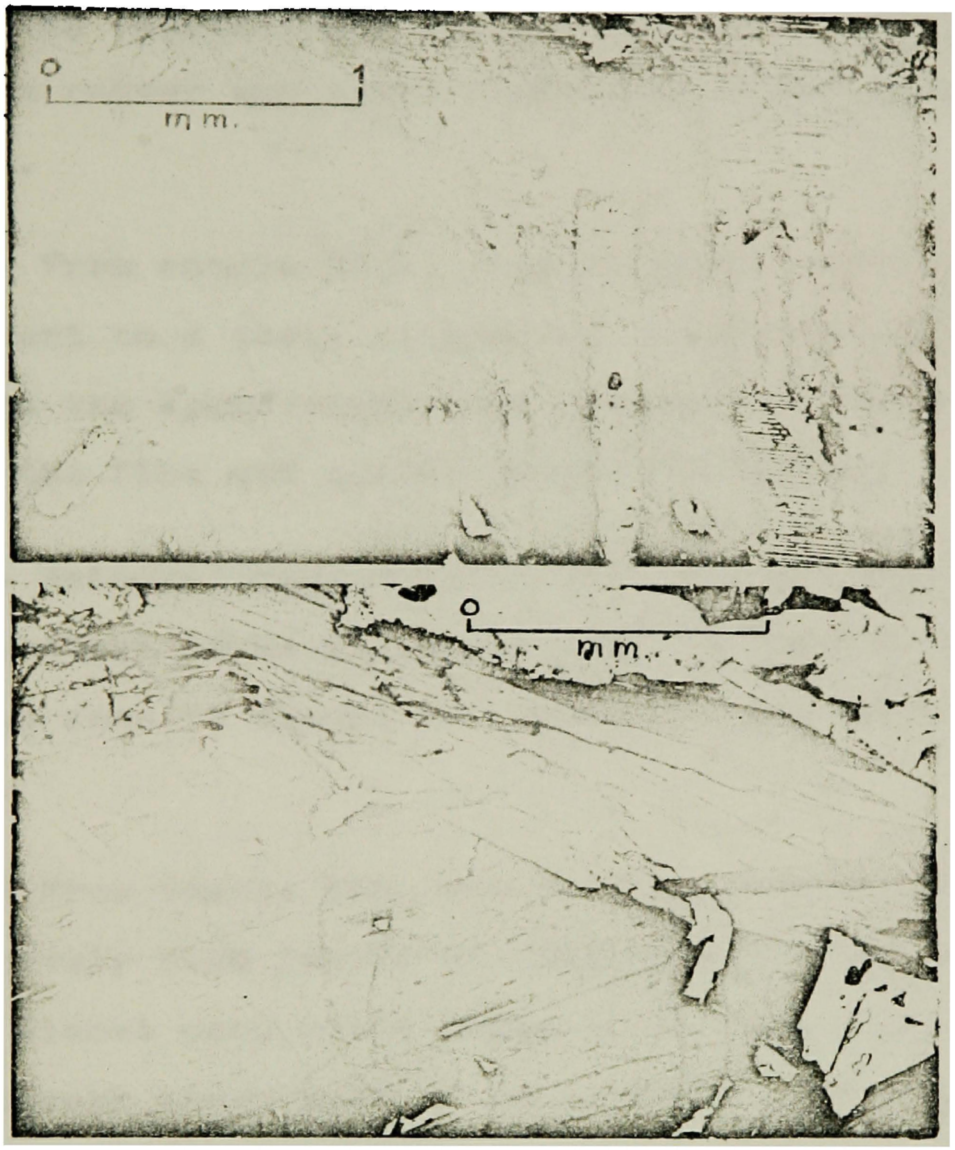


Plate 2



a

b

Plate 2a - From sample IV 6, a twinned plagioclase megacryst at the core of a composite orbicule (right half of the photograph) has served to nucleate plagioclase laths of the first shell of the orbicule (left half of the photograph).

Plate 2b - In sample V 4b, biotite forms a distinct rim around a hornblende megacryst.

Plate 3a - Zoned plagioclase grain in sample II29a with twinning lamellae and sericitized core. Grains at bottom center and upper right also show altered cores.

Plate 3b - From sample SR3a, this myrmekite developed adjacent to a large microcline porphyroblast which covers the upper right-hand portion of the photo. Note the fine and coarse vermicular quartz.

Plate 3c - Anhedral quartz fills void between adjacent plagioclase laths in sample I59. A similar texture can be seen in Figure 8. Quartz is not part of a vein.

Plate 3d - From sample I59, the lighter grains with relatively high relief are amphiboles which have been almost completely replaced by carbonate. Photograph shows part of an orbicule core which is almost entirely biotite.

Plate 3

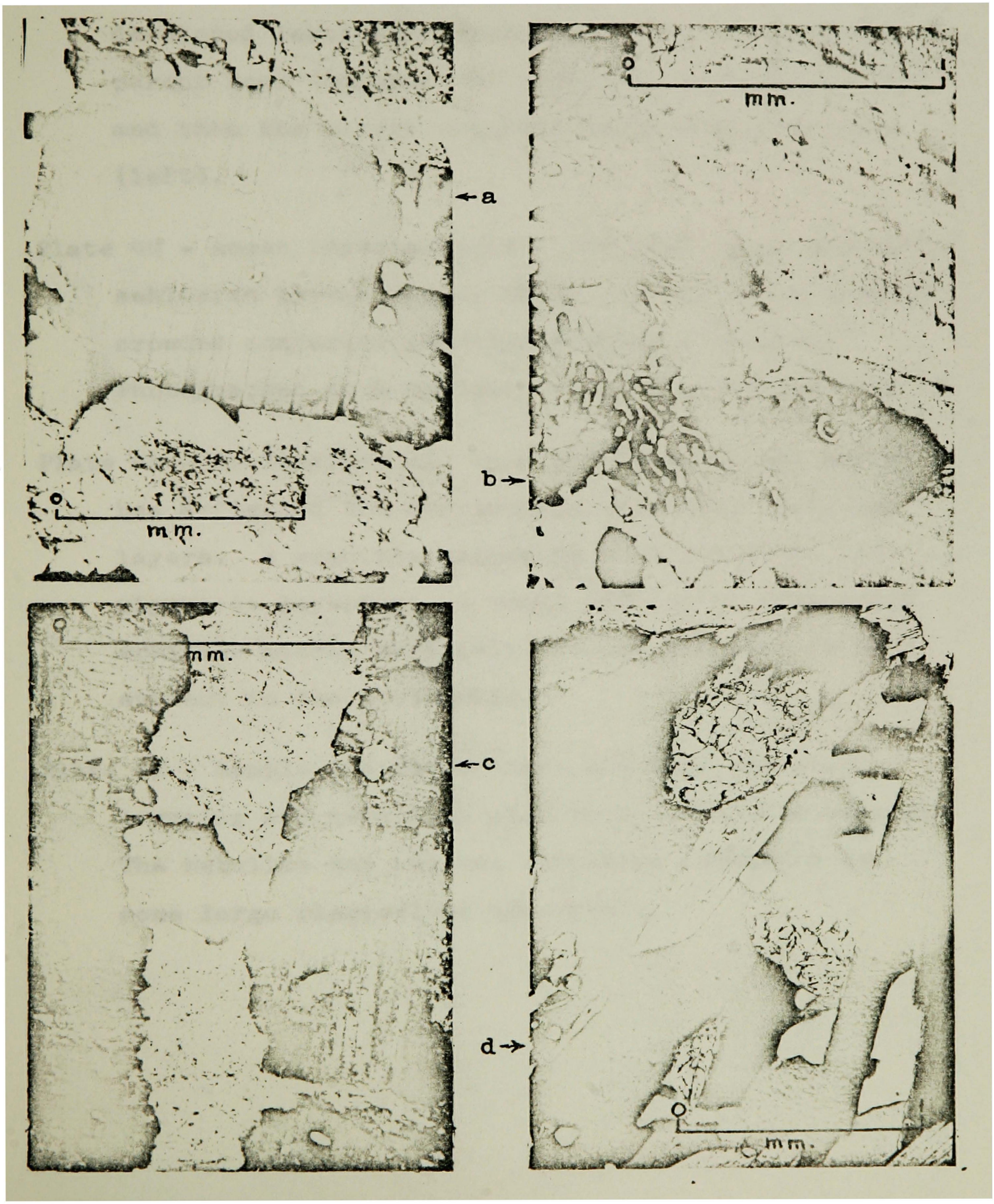


Plate 4a - Migmatite in sample II7b appears to have first developed lenticular stromatic layers from within the parent rock (adjacent to darker right-hand portion) and then the layers expanded developing schlieren (left).

Plate 4b - Augen layering (above the hand lens) parallels schlieren layers (upper right corner) and a zone of crowded composite and thin-shelled orbicules. Photographed on a boulder excavated from locality II.

Plate 4c - At locality II, this multiple-shelled orbicule has deflected the surrounding, elongate schlieren layers. A granitic pegmatite vein transects the migmatite layering. A small portion of fragmental orbicule matrix parallels the layering but is not evident in the photograph.

Plate 4d - Sample I36 shows light and dark migmatite layering and nebulitic structure (bottom of sample). The nebulite has several schistose fragments and some large plagioclase megacrysts.

Plate 4

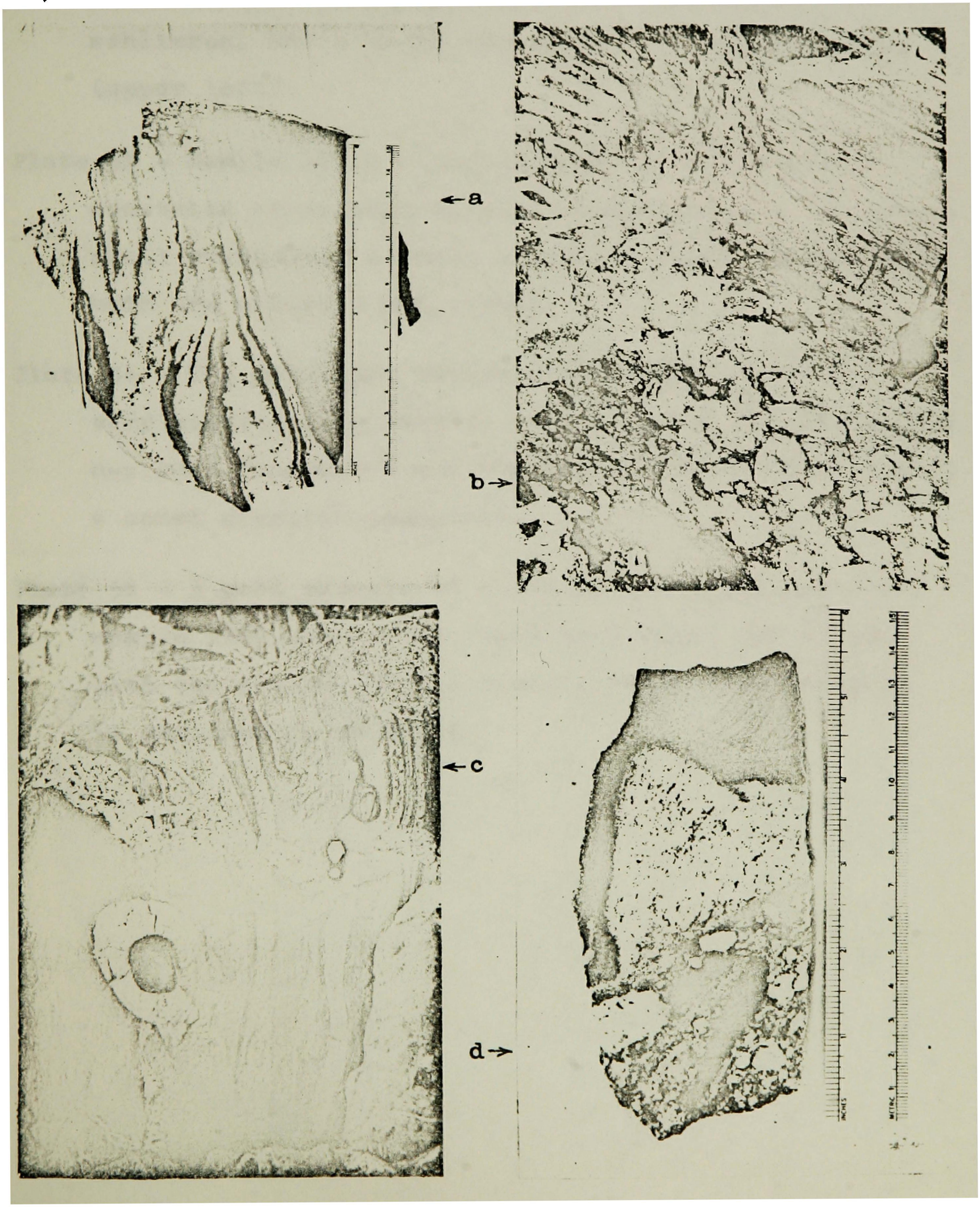


Plate 5a - Taken at the roadcut in locality III, the photo shows a flat, thin-shelled orbicule, several dark schlieren, and a large cross-cutting pegmatite vein (upper left).

Plate 5b - Sample I2 is a thin-shelled orbicule with a quartzite core; magnetite is concentrated at the core-shell boundary. A small pegmatite veinlet penetrates both the orbicule and matrix.

Plate 5c - The composite orbicule in sample I58 lies in a very biotite-rich matrix. The orb, but not its matrix, has been fractured, and the orb matrix has been cut by a zoned granitic pegmatite.

Plate 5d - A good example of a multiple-shelled orbicule, sample II49 also shows fracturing which has offset both the shells and the biotite core. The fracture is enriched in chlorite.

Plate 5

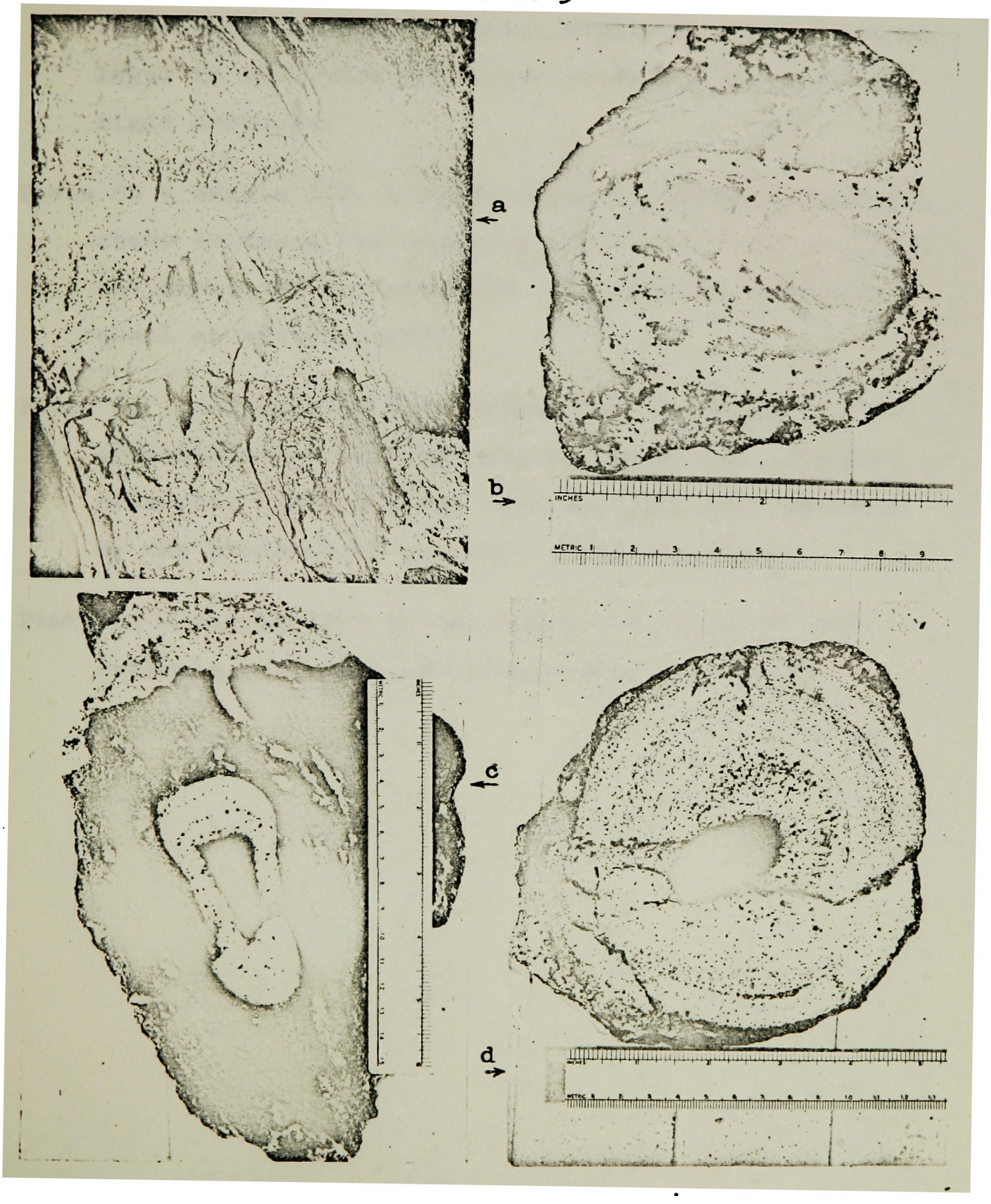


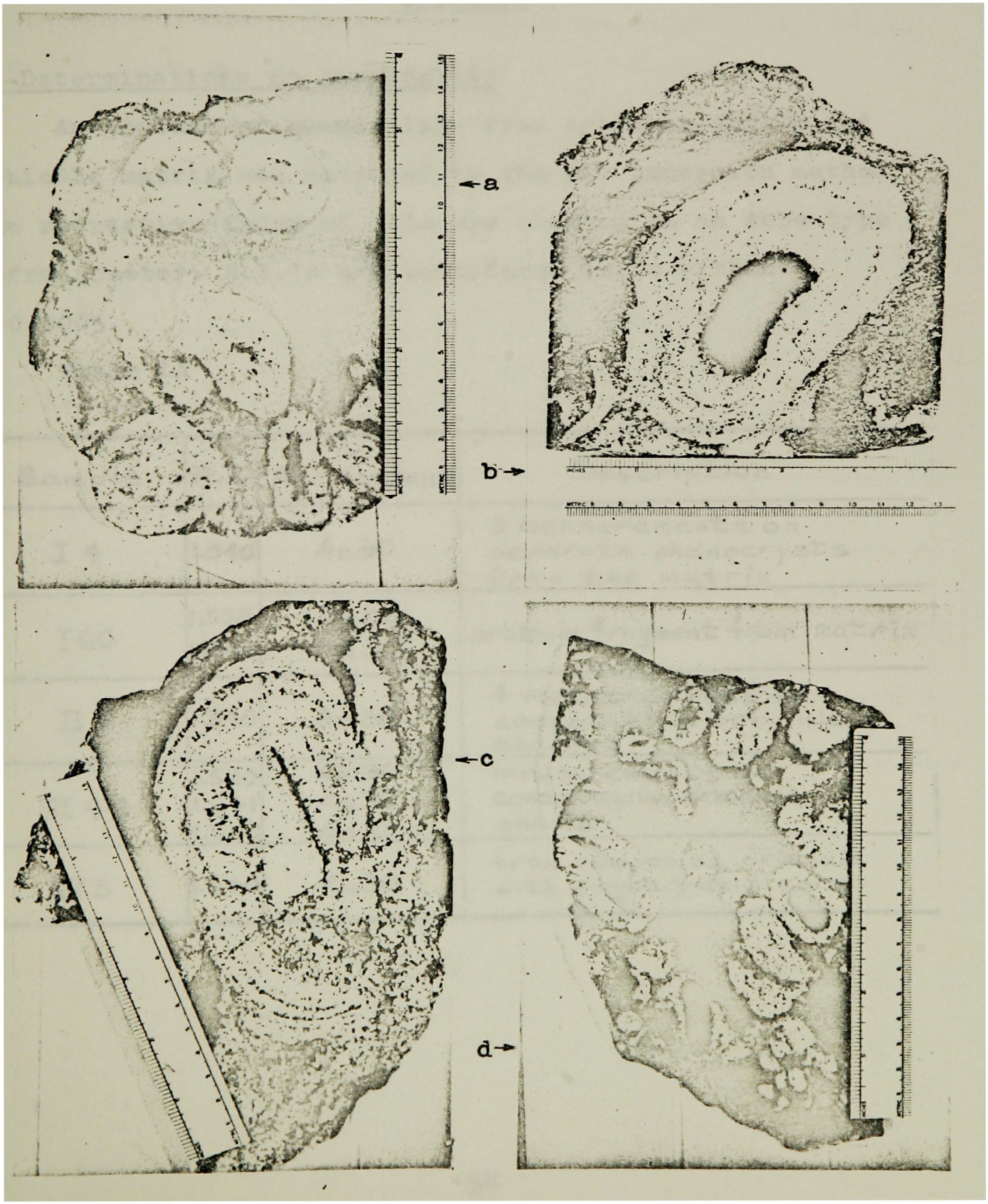
Plate 6a - Composite orbicules in sample IV have nucleated on megacrysts and xenolithic fragments. A schlieren layer in the upper right has conformed to the more-rigid orbicule.

Plate 6b - Sample II2, a large multiple-shelled orbicule, shows evidence for shearing (fracture through shells and core) and for abrasion (fragment of outermost shell at bottom left).

Plate 6c - Sample II55 is a large orbicule which has crystallized on a fragment of a previously-formed orbicule. This orb has been subsequently fractured by the invasion of granitic pegmatite veins.

Plate 6d - Sample II47 is an orbiculite littered with orbicule fragments and plagioclase megacrysts.

Plate 6



APPENDIX

An-Determinations on Plagioclase

An-content of plagioclase from orbicule shells and orbicule matrix was measured by the oil immersion method The refractive index of oils was checked on an Abbe-type refractometer; R.I.'s are considered to be within ± 0.0005.

Table 1A

Sample	R.I.	An-Content	Description
I 4	1.540	An30	3 measurements on separate phenocrysts from the matrix
I 60	1.538 1.540	An 28 An 30	orbicule fragment from matrix
II 7	1.540	An 30	4 measurements on consecutive orbicule shells
II 49	1.540 1.541 1.540	An 30 An 31 An 30	measurements on consecutive orbicule shells
IV 5	1.540	An30	from composite orbicule with megacrystic core

Number of Orbicule Shells and Shell Spacing

The number of orb shells, thickness of shells, and distance between successive shells were measured from sawed slabs on the longest axis of the orbicule.

Table 2A

Sample	Number of Shells	Shell Spacing	Thicknesses in mm. Beginning at Core
I 58	5	not determ., orb severely fractured	23
I 59	7	random	28
II 4a	7	random	52
II 6a	11	random	70
II 7	11	outer three shells 1 cm.	65
II 49	8	random	64
II 55	7	random	40

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